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Volume 8 APRIL, 1938 Number 1

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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The subscription price of the JOURNAL OF SEDIMENTARY PETROLOGY is $3.00 per year prepaid to addresses in the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Bolivia, Colombia, Honduras, Nicaragua, Peru, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands.

Single numbers, $1.50 each.

Postage is charged extra: For Canada, 20 cents on annual subscriptions (total $3.20), and for all other countries in the Postal Union, 40 cents on annual subscriptions (total $3.40).

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Communications about the JOURNAL, subscriptions, rates, memberships, change of address, advertising and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P. O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

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Journal of Sedimentary Petrology

VOLUME 8

APRIL, 1938-DECEMBER, 1938

Nos. 1-3

W. H. TWENHOFEL, EDITOR

PUBLISHED BY THE

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

A DIVISION OF

THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 1, PP. 3–9, FIGS. 1–2, APRIL, 1938

RECORDING THE RESULTS OF HEAVY MINERAL ANALYSES

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ABSTRACT

Two diagrammatic methods of expressing the results of heavy mineral analyses are illustrated by data obtained from the examination of a series of soils from the Western Australian gold fields. A brief description is given of the preparation of soils for the microscopic identification of mineral grains.

The writer has lately been engaged in a mineralogical examination of soils from the Southern Cross and Kalgoorlie centers of the West Australian gold fields (*Geol. Mag.*, vol. 73, no. 869, 1936) and during the course of the investigation the matter of presenting the results of the heavy mineral analyses has necessarily been considered rather fully, for the value of any such investigation depends upon the "availability" of the data. The results of studies of sedimentary material published in many papers are only too often obscured by columns of figures which few readers feel willing to peruse or to try to interpret.

This paper describes the technique adopted for the mineralogical examination of soils, and discusses and illustrates methods for the presentation of the data.

SETTING OF THE INVESTIGATION

The interior of Western Australia is a more or less flat, high-level plain whose underlying rocks, pre-Cambrian in age, are largely obscured by soil. Hence many possibly auriferous rocks are hidden from both prospector and geologist.

The soils investigated were collected from sites where the gradation between solid rock and surface soil could be seen, so that the heavy minerals examined would be "standard" and could later be used for purposes of comparison. The identification of soils derived from greenstones was one of the principal objectives for these rocks are the main gold-bearing series of this part of the state, and it is hoped that the identification from soil samples of hidden areas of greenstone may be of material assistance to geologists and gold-miners.

LABORATORY TREATMENT

Previous experience with soils had shown that, of the various grades of material given by mechanical analysis, the fine sand (0.2 to 0.02 mm) of the standard International Mechanical Soil Analysis (11, 13) gave grain sizes most suitable for the microscopic identification of minerals. The fine sand fractions were obtained by sieving and by elutriation with an Andrews' Kinetic Elutriator. The sieve used to separate the fine from the coarse sand was an 85-mesh B.E.S., which approximates the 70-mesh I.M.M. sieve. The coarse and very fine grains of the soils were discarded and the results discussed refer only to the fine sand fractions.

In a natural state the soils are bright reddish-brown to red in color, and on inspection the grains of the fine sands were found to be coated with ferruginous and aluminous material. This was removed by boiling in 1:1 conc. HCl.

The heavy minerals, i.e., those sinking in bromoform, were concentrated by bromoform separation. These separations were carried out more successfully by placing the bromoform in evaporating dishes than by using glass funnels fitted with rubber tubing as recommended by British workers, for in the latter method an appreciable quantity of the residue is lost through grains sticking to the sides of the funnels. The percentage weight of the heavy minerals of many samples was found by weighing the fine sand be-

fore separation and weighing the "light fraction" afterwards. This is the *Index Figure* of Groves (8, 236). Occasionally a further separation of the heavy min erals was made with Clerici solution of Sp. Gr. 3.5 to 3.7 to help in the identification of some particular species.

The heavy minerals were next mounted in clove oil (R.I. about 1.53) for preliminary identification. Mounts containing grains not readily identified were re-mounted in liquids of higher refractive index, such as α-chloronaphthalene, α-bromonaphthalene, and methylene iodide, or mixtures of these, until identification of all the minerals was completed. Then permanent mounts of the heavy minerals in Canada balsam were made.

COMPOSITION OF THE HEAVY MINERAL ASSEMBLAGES

Counting the grains of each species seen in a number of traverses across a "fair-average quality" part of each slide gave the percentage mineral composition of the samples. The counting was facilitated by using a mechanical stage. The "f.a.q." percentages give a fairly definite idea of the relative abundance of any mineral in the assemblages, but they fail to take account of an important characteristic of the fine sands, viz., the index figure, or per cent by weight of the heavy minerals. For example, one sample, A, may contain 10 per cent of a certain mineral, but the index-figure is small; another sample, B, contains 5 per cent of the same mineral, but the index figure is three times that of A; so that B actually contains a greater amount of the mineral, although this would not be apparent from the percentage composition alone.

In comparing sediments by examining the heavy minerals, it is necessary to know, as accurately as possible, the relative amounts of the minerals present. From the time that mineralogists began to be interested in this phase of geology there have been differences of opinion as to how these relative amounts should be obtained and recorded. The position has been discussed by Boswell (2, Chap. VI) and summarised by Milner (10, 384–388), and the general opinion now is that when the time and the nature of the investigation allow, a count of the grains of part at least of a heavy mineral assemblage is preferable to visual estimation of the proportional occurrences of minerals. It must be realized, however, that in the examination of a large number of samples counting, involving as it does close application, is often impracticable because of the time required, and also because of the mental fatigue and consequent liability to error produced by this rather monotonous occupation.

Dr. W. F. Fleet (7) was the first to express the mineral composition of an assemblage by counting the grains and reducing the figures to percentages, and he still considers this method satisfactory (personal communication) in spite of cautionary remarks by Dryden (3), who points out that when considered statistically percentages are not as accurate as they appear to be, because "in a count of a number of grains, the probable error of the abundant species will be much lower than that of the rarer ones." Dryden states, "In general, the accuracy (of the percentage figures) increases as $\sqrt{n}$ (n = total number of grains counted) so that if twice the accuracy is desired four times as many grains must be counted." He calculates that to state the percentage of a mineral comprising about half the count as 50 ± 1 per cent, 4,549 grains would have to be counted whereas a count of 200 grains gives 50 ± 5 per cent for the same mineral. As 500 was the average count in this series of samples, the percentages for the most abundant minerals are correctly given as ± 3 per cent, but the figures for the rarer species are much less reliable. In practice, accuracy to much less than 5 per cent error is not considered advisable because of variation in mineral composition of the same deposit in different localities.

EXPRESSING THE RESULTS

As was expected from the method of collecting the soils from Southern Cross, the heavy minerals included species which gave definite indications of parentage.

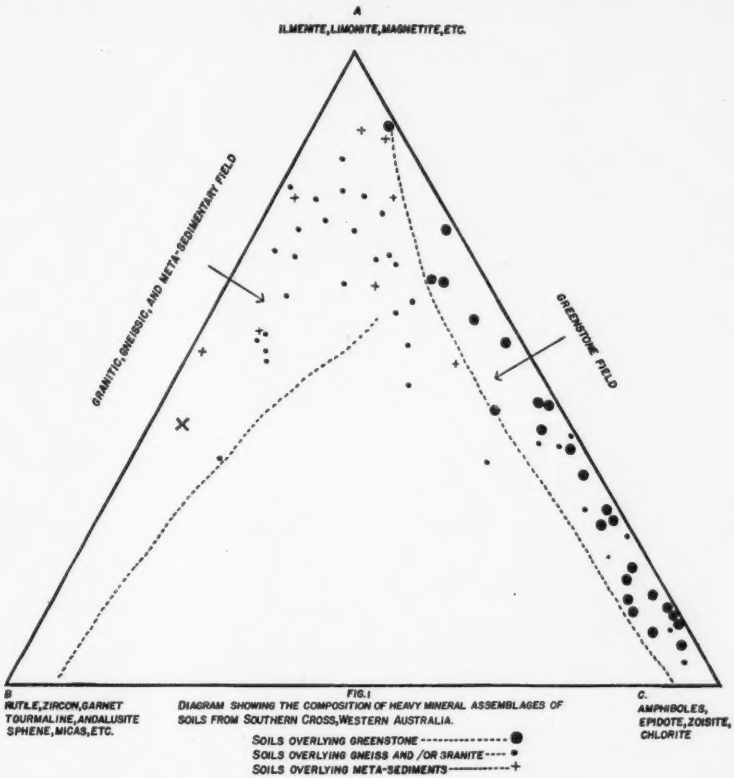

FIG. 1
DIAGRAM SHOWING THE COMPOSITION OF HEAVY MINERAL ASSEMBLAGES OF SOILS FROM SOUTHERN CROSS, WESTERN AUSTRALIA.

soils which can usually be distinguished from one another in the field. From a study of the accessory minerals of crushed rocks it was found that the granitic types yielded zircon, sphene, apatite, tourmaline, micas, rutile, and garnet. The greenstones, which range from amphibole schists to epidiorites, yielded an abundance of several varieties of amphibole, with small amounts of epidote, zoisite, rutile, and chlorite. In the meta-sediments, andalusite, garnet, and micas are common and sillimanite, staurolite, and rutile are often present.

The country rocks of the Southern Cross district can, broadly, be divided into three types: granites and gneisses; greenstones; and meta-sediments. The distinction between the granitic gneisses and those of metamorphic origin is often difficult to draw, but the latter are often garnetiferous. The rocks are of pre-Cambrian age and have weathered to

The same minerals are found in the

soils where they are invariably accompanied by ilmenite, limonite, and magnetite. The latter are by no means absent from the source-rocks but are much more conspicuous in the soils than in the rocks; this is due to weathering and soil-forming processes.

In order to interpret the results of this investigation Dr. A. Brammall, Imperial College of Science and Technology, London, suggested that the heavy minerals of each soil could be grouped according to origin, and then plotted in a triangular diagram similar to that used to express the mechanical composition of sediments (9, 226, 472) (fig. 1).

As the soils overlying greenstones contained abundant amphibole, one pole of the diagram, *C*, was allotted to amphiboles, epidote, zoisite, and chlorite, all of which are minerals connected with this type of rock. *C* can therefore be called the "greenstone pole."

Difficulties arose, however, in making a distinction between minerals common to the granites and gneisses, and those common to the meta-sedimentary series. Zircon, sphene, micas, rutile, tourmaline, and garnet are likely to occur in any of these rocks, so that it was not considered practicable to make too fine a distinction between these soils of different but allied parentage. As the main point of the investigation was the recognition of greenstone or non-greenstone parentage of the soils, the writer, in consultation with Doctor Brammall, decided to place the minerals derived from granites, gneisses, and meta-sediments at pole *B*, leaving one pole, *A*, to be filled by the opaque minerals such as ilmenite, magnetite, limonite, hematite, etc. Although these opaque grains are present in all the soils, their relative abundance is a guide to greenstone or non-greenstone parentage. The soils derived from greenstones situated near *A*, or half-way between *A* and *C* have resulted from the weathering of epidiorites, whereas the analyses at or near *C* are of soils originating from amphibole schists.

The groups into which the minerals were divided are:—

A. Ilmenite, limonite, magnetite, hematite, and other opaque grains.

B. Rutile, tourmaline, sphene, zircon, micas, andalusite, garnet, and any other species of minor importance.

C. Amphiboles, zoisite, epidote, chlorite.

A, *B*, and *C* correspond to the poles of the diagram in which the percentages are plotted. The data were arranged thus:

	A %	*B* %	*C* %
Sample			
12165	72	—	28
12191	6	—	94
15896	53	4	43

and similarly for all soils from the area (% = % of total heavy minerals).

In the diagram the analyses of soils of greenstone origin are grouped along the side *A*–*C*, the points nearest *C* representing soils derived from amphibole schists. When all the analyses are considered a narrow "greenstone field" is found in the position shown. All analyses of heavy minerals of soils from this district which fall within this field will be either soils directly derived from greenstone or soils of other parentage badly contaminated with material from the greenstones. The presence near *C* of soils known from field evidence to overlie gneiss illustrates this point. The abundance of ilmenite and other opaque species in the residues of soils of non-greenstone origin has caused these analyses to congregate toward the apex of the triangle, but the writer is at present examining another series of soils from this district, the analyses of which will fall along the side *A*–*B*, somewhere near *X*. The field occupied by the soils of non-greenstone origin is not so clearly defined as the "greenstone field," but is approximately in the position indicated. Soils of thoroughly mixed parentage will fall near the center of the triangle, but

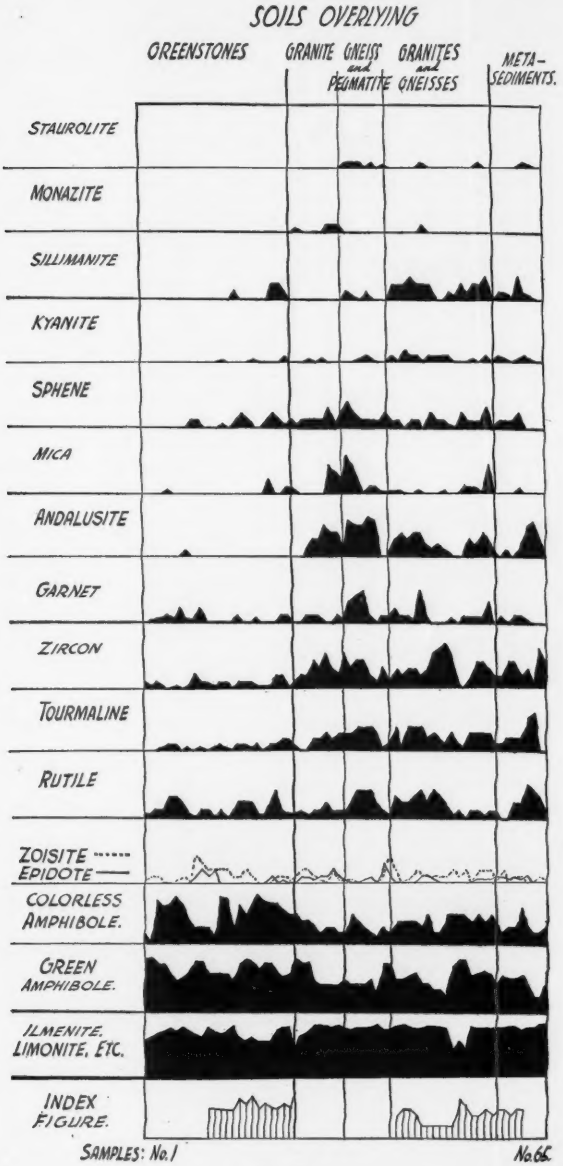
SOILS OVERLYING
GREENSTONES
GRANITE GNEISS and PEGMATITE
GRANITES and GNEISSES
META-SEDIMENTS.
STAUROLITE
MONAZITE
SILLIMANITE
KYANITE
SPHENE
MICA
ANDALUSITE
GARNET
ZIRCON
TOURMALINE
RUTILE
ZOISITE
EPIDOTE
COLORLESS AMPHIBOLE.
GREEN AMPHIBOLE.
ILMENITE. LIMONITE, ETC.
INDEX FIGURE.
SAMPLES: No. 1
No. 66.

FIG. 2

because of the opaque minerals, somewhat towards the apex.

By plotting the mineralogical analyses of other soils from this area where the rocks are invisible one could, the writer believes, tell confidently the parentage of the soils.

OTHER METHODS OF PRESENTING THE DATA

The Burmah Oil Company method (6, 251) can also be used to record the results of this investigation. For this the percentage figures are tabulated as frequency numbers, and then these are used to make a graph or "Range Table." The Burmah Oil Company has found this method satisfactory for recording observations made by a number of persons working independently on the same problem, e.g., oil-field correlations. The information is readily interpreted as a glance at the Range Table for the Southern Cross soils will show (fig. 2).

The percentages are given the following frequency numbers:

Percentage	*Frequency Number*
90–100	8+
75–89	8
60–74	8−
45–59	7+
35–44	7
28–34	7−
23–27	6+
18–22	6
14–17	6−
7–13	5
4–6	4
2–3	3
1–2	2
½–1	1
one grain only	1[a]

Except for the lowest numbers, this "scale is a geometric progression, and, in plotting, one square of paper ruled to one-tenth inch is taken for each frequency number, thus giving a truly logarithmic scale except for the lowest numbers." The resulting graph, in which each mineral is plotted separately, is known as a Range Table. The same figures were used for the range table of the Southern Cross soils as for the triangular diagram. The index figure for each soil was added to the range table in order to make the information as complete as possible. The table shows clearly the differences between soils of greenstone and non-greenstone origin. Another advantage of using this method of plotting is that the "results are in consonance with the degree of accuracy and uniformity inherent in the analyses and for this reason direct percentages are not recommended." This scale of frequency numbers is a great improvement on the figures suggested and used by Milner and others (10, 384–388), as the numbers have a definite percentage range.

As far as the writer is aware, no completely satisfactory statistical method for indicating the relationships of samples containing a large number of items has yet been evolved. Dryden (4) proposed using the correlation coefficient as a measure of the similarity of the various mineral proportions in the samples he compared; but Eisenhart (5) criticised Dryden on the grounds that the "correlation coefficient" is not applicable to samples classified in respect to mineral composition." He suggested using the Chi-Square Test "to indicate whether a given deposit is homogenous in the statistical sense, and it will also indicate when applied to several deposits whether they can be considered as mutually homogenous."

Both these methods were tried on the analyses of the Southern Cross soils, but to work through a large number of samples in this way would take a great deal more time than the results ultimately achieved warrant, although in some investigations the correlation coefficient, r, or rather the coefficient of determination r^2, gives a neat figure for comparing samples. Dryden (4, 407) states that such refined methods of correlation are only suitably used for samples collected in close proximity to one another, e.g., samples taken an inch apart across the boundary of two beds. For the more usual type of heavy mineral investigation in which the samples are collected over a wide area the information conveyed by percentage figures or

diagrams is sufficiently precise. The investigation described here is of the latter type. It must be remembered that in all such investigations there are unavoidable errors in the collection and laboratory treatment of samples, however careful one is, and therefore the accuracy of the final figures should not be more apparent than real.

An important characteristic of mineral grains is the variation in habit and appearance of the same mineral in different environments, i.e., sediments of various ages probably will not contain species of identical appearance. As everyone who has studied the mineralogy of sediments knows, two heavy fractions may each contain 5 per cent of, say zircon; in *A*, the zircons are tawny, zoned and angular, whereas in *B* the grains are rounded and water-clear. From which it is inferred that the distributive provinces were not similar, although the figures for zircon, and even for the other minerals in the samples, may be practically the same. These samples must, therefore, be of different origin, and the same principle will apply to soils.

I am greatly indebted to Doctor Brammall for bringing the importance of the varietal features of mineral grains to my notice. He had previously stressed this aspect of sedimentary petrology in his masterly paper on the Dartmoor detritals (1), and no mineralogical examination of sediments should be considered complete without a record of and interpretation of the significant varietal features of the heavy minerals. In this paper, written solely to show how the information contained in a series of percentage results can be illustrated by diagrams, no attempt has been made to describe the varietal features of the minerals. A summary of this part of the study has already appeared in the Geological Magazine.

CONCLUSIONS

The triangular diagram and the range table for the heavy minerals of soils from the Southern Cross district of Western Australia serve to indicate that these two methods of illustrating the information supplied by the percentage compositions of heavy fractions can be usefully applied where the investigation is of a preliminary or reconnaissance nature.

ACKNOWLEDGMENTS

I wish to express my great appreciation of the help and advice given by Prof. E. de C. Clarke, University of Western Australia, who suggested this investigation. In the later stages of the work I have had many invaluable discussions with Dr. A. Brammall, Imperial College of Science and Technology, London, to whom I am also deeply grateful.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 1, PP. 10–18, FIGS. 1–3, APRIL, 1938

STUDIES ON THE BACTERIAL FLORA OF MARINE BOTTOM SEDIMENTS

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Contributions from the Scripps Institution of Oceanography, New Series No. 2

ABSTRACT

The bacteriological analysis of 126 sediment samples collected in the Channel Island region along the coast of Southern California from bottoms as deep as 2,000 meters reveals the presence of several physiological types of bacteria which may influence the diagenesis of recent sediments. Strict aerobes recovered from the bottoms of cores over 50 cm long where there is no free oxygen may have been buried in the sediments in a dormant state for a long time. Core depth, organic-matter content, and the median particle size of the sediments are the chief factors which influence the bacterial populations. Most of the bacteria are capable of multiplication and biochemical activity at 0° C. Bacteria which decompose proteins, cellulose, starch, chitin, and other complex organic compounds are quite abundant in the bottom deposits. The occurrence of lipoclastic species which utilize the glycerol from fats and leave long-chain fatty acids may help account for the genesis of petroleum.

The fragmentary literature on the subject indicates that bacteria and closely related micro-organisms play an important role in the diagenesis of marine bottom deposits. They are endowed with the ability to modify the chemical composition, physical characteristics, and biocoenosis of recent sediments (Twenhofel, 1932, p. 147). Perhaps bacteria have a greater influence than any other form of life upon the hydrogen-ion concentration, oxidation-reduction potential, color, occurrence of sulfur compounds (Galliher, 1933), and organic-matter content of marine sediments.

However, popular literature still records that in the deep water off the continental shelves the high hydrostatic pressure and low temperature are inimical to the existence and activity of bacteria. Inasmuch as over four-fifths of the ocean floor exceeds one mile in depth and is perpetually colder than 3° C, it is significant that ZoBell (1934) has described several types of marine bacteria which are capable of multiplication and metabolism at temperatures lower than 0° C. Drew (1914), Lloyd (1931), Waksman et al. (1933), Reuszer (1933), ZoBell and Anderson (1936a), and others have demonstrated the presence of bacteria in bottom deposits wherever samples have been taken regardless of the water depth or the distance from land.

This report is primarily concerned with the quantitative estimation of bacteria in marine bottom deposits in the Channel Island region along the coast of southern California. Particular emphasis is placed upon the demonstration of bacteria whose biochemical activities may geologically modify their environment.

EXPERIMENTAL

Numerous cores of mud 4 cm. in diameter and 20 to 90 cm. long were collected from water depths ranging from a few meters to over 2,000 meters. The samples were collected by means of a modified Ekman mud-sampling device (fig. 1). Uncontaminated 3 to 6 gram sub-samples were dissected from the center of the cores (fig. 2) and weighed into tared bottles containing 50 cc. of sterile sea water. The sediment was suspended by shaking the bottles, after which aliquot parts were bacteriologically analyzed. Conventional soil microbiological procedures (Fred and Waksman, 1928) were used.

The total number of bacteria was de-

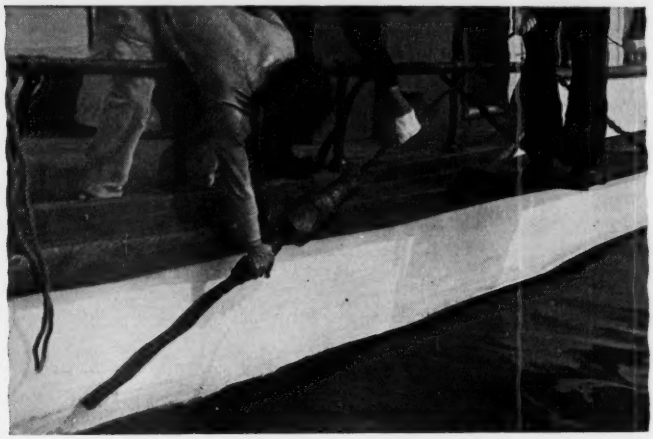

FIG. 1.—Modified Ekman coring device being lowered over the side of the boat SCRIPPS. It consists of a steel pipe 1½ in. in diameter and 3 to 6 ft. long sharpened to a knife-edge. The lowest hand shows the position of the stop-valve which permits water to escape from the pipe as it is driven into the mud by the 60 lb. lead weight. The 10 ft. rod to which is attached the cable serves to lower the center of gravity of the apparatus when it is suspended in the water and thus helps to keep the corer from tipping over when it strikes the sea bottom.

termined by the plate count method using a nutrient medium containing 0.3 per cent Bacto-peptone, 0.2 per cent each proteose-peptone and beef-extract, 0.025 per cent $FeCl_3 \cdot 6H_2O$ and 1.2 per cent agar. The reaction was adjusted to pH 7.6 with 1/N NaOH after autoclave sterilization. A similar nutrient medium containing only 0.3 per cent agar was employed to estimate total numbers of bacteria by the minimum dilution method (Halvorson and Ziegler, 1933). This latter enumeration procedure failed to give counts which were appreciably higher than the plate counts and since the standard deviation of duplicates was much greater than plate counts, the routine use of the minimum dilution method was confined to the estimation of the relative abundance of certain phys-

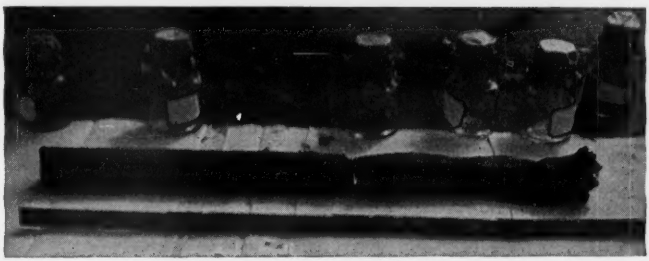

FIG. 2.—A 20-inch sediment core and the tared wide-mouth bottles to which sub-samples from different strata are transferred for bacteriological analysis. The topmost 2 inches of the core which was semi-fluid has been placed in the bottle on the right.

iological types of bacteria. The results from direct microscopic counts were not encouraging because the colloidal detritus and salt content of the sediment interfered with the fixation and staining procedures. However, direct counts revealed the presence of from ten to forty times as many bacteria as were shown by plate counts although the standard deviation on duplicate direct counts was extremely high.

acteristics. After its storage for a month or two only three or four predominating kinds of bacteria remain in mud which initially contained thirty to fifty different kinds. These changes occur more rapidly when the samples are stored at room temperature than at refrigeration temperatures.

Incidentally neither the magnitude nor the rate of change in the bacterial flora

TABLE 1. *The effect of storage at 0 to 4°C on the bacterial population of sediment samples (samples were collected at Station No. 36 E 1 [32°42.5′N. and 117°27′W.] where the overlying water is 608 meters deep)*

Sample No.	9829	9830	9849	Number of different types of colonies
Storage time	Bacteria per gram (wet basis)			
<1 hour	2,910,000	1,680,000	3,000,000	47
24 hours	3,300,000	3,500,000	5,200,000	44
48 hours	4,000,000	6,700,000	8,100,000	40
7 days	12,500,000	25,000,000	15,700,000	18
12 days	38,200,000	30,000,000	12,000,000	16
24 days	59,300,000	19,000,000	22,300,000	9
44 days	16,400,000	12,100,000	7,300,000	7
90 days	17,400,000	11,700,000	6,150,000	3

In most cases the samples were analyzed within a few hours after collection. When it was necessary to hold them overnight before analysis, the samples were kept in a refrigerator near 0° C. This point is emphasized because in some cases circumstances have prevented investigators from analyzing their mud samples for several days or even months after collection. The storage of samples is accompanied by quantitative and qualitative changes in the bacterial flora of considerable magnitude. This is illustrated by the data in table 1 which show that the total number of bacteria increases and later decreases during the storage of bottom deposits at refrigeration temperature. There is a progressive decrease in the number of different kinds of bacteria as indicated by colony char-

of bottom deposits during storage is nearly as great as in sea water. ZoBell and Anderson (1936b) found that the bacterial population of sea water in the Channel Island region which initially contains only a few to a few hundred bacteria per cc. increases during a week or two of storage to hundreds of thousands or millions of bacteria per cc. This difference is attributed to the more advanced stage of decomposition of the organic matter in bottom deposits. There is much more organic matter per unit volume in bottom deposits than in the water but it is much less readily utilized by bacteria than that in the overlying water. This conclusion is substantiated by observations on the biological oxygen demand of samples of water and sediments to be described elsewhere.

Table 1 also presents evidence that bottom-dwelling bacteria multiply at low temperatures. In fact, almost as many colonies developed on nutrient agar plates which were incubated in the refrigerator at 0 to 4°C as on similarly inoculated plates which were incubated at higher temperatures. However, the bacteria multiply very slowly at the low temperatures, several weeks being required for some of them to form macroscopically visible colonies. The optimum temperature for the growth of most marine bacteria, including those which come from bottoms where the temperature is perpetually colder than 5°C, was found to be between 20° and 25°C. In the routine analysis of bottom deposits the plates were incubated at 22°C until the counts approached constancy which usually requires from five to seven days.

Observations on the vertical distribution of bacteria in bottom sediments reveal that the largest bacterial populations occur in the upper layers of the cores. It is difficult to follow stratification in the topmost 3 to 5 cm. of the cores because of the loose consistency of this sedimentary material, but at greater depths the cores consist of firm well-packed sediments which clearly show stratification (fig. 2). Probably the zone of greatest bacterial activity in the sea is within the topmost few millimeters of aqueous colloid-rich ooze which constitutes the so-called "mobile layer." In over a hundred samples which have been analyzed, from a few thousand to several million bacteria per gram of mud (wet basis) were found in the upper 5 cm. layer. Below the 5 cm. zone the bacterial population decreases sharply with depth as shown by fig. 3. There is a relationship between the vertical distribution of bacteria in the cores and the organic matter content of the sediments, Moberg et al. (1937), having found that the organic matter content of these same cores also decreases with depth.

Aerobes greatly outnumber anaerobes near the top of the cores. Both decrease rapidly with core depth, the former more rapidly than the latter, so at core depths exceeding 20 to 40 cm. anaerobes usually predominate. Aerobes are defined as those bacteria which reproduce in the presence of free oxygen and anerobes are those which reproduce in the absence of free oxygen. Some of these microorganisms are facultative anaerobes

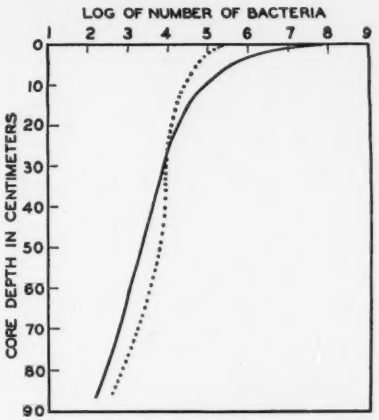

FIG. 3.—The vertical distribution of aerobic (solid line) and anaerobic (dotted line) bacteria in marine bottom deposits.

which are capable of reproduction either in the presence or absence of free oxygen and hence they will be counted both as aerobes and as anaerobes. While tests on isolated pure cultures demonstrate that strict aerobes as well as strict anaerobes occur in core strata from all depths, it is not practicable to enumerate them.

The presence of strict aerobes in the sediments at great depths merits special attention because here there is no available oxygen present. According to ZoBell and Anderson (1936a) these sediments actually have an oxygen deficit as shown by their oxygen-absorbing capacity and their low oxidation-reduction potentials. The extreme reducing conditions of the sediments below the 5 cm. zone would permit the multiplication of only anaer-

obes. This must mean that the viable aerobes have been buried there by sedimentation in a dormant state or else they have been carried deep into the sediments by burrowing organisms or other agencies. When the data on the vertical distribution of aerobes below the upper 10 cm. zone of rapid transition are treated statistically, they fit a logarithmic curve which is typical for the order of death of bacteria (Rahn, 1932) when the survivors are plotted against time (core depth to represent time in fig. 3). Similarly Henrici and McCoy (1937) found that profile series of bacteria from lake bottom deposits give logarithmic death curves. This is believed to indicate that the aerobes are slowly dying off below the 5 to 10 cm. level. The sigmoid curve which depicts the vertical distribution of anaerobes suggests that these bacteria are active to depths of 40 to 50 cm. below which they seem to be slowly dying.

Neither distance from the mainland nor depth of the overlying water seems to have any influence upon the bacterial population of the bottom deposits. However, this limited survey includes samples from distances no greater than 120 miles from the mainland and depths no greater than 2,009 meters. In deeper water where less organic matter from above would reach the bottom, fewer bacteria may be present in the bottom deposits. There is no evidence that either the number or kind of bacteria is influenced by seasonal cycles.

Relatively small numbers of bacteria occur in the coarse sand which usually characterizes the littoral zone. However, the number is more closely related to the character of the sediments than to their distance from land because as a rule sand contains fewer bacteria than sediments consisting chiefly of smaller particles regardless of their topographical position. Table 2 shows the average number of bacteria found in different types of bottom deposits. The scheme for classifying the sediments as sand, silt, clay or colloid according to the median particle size is taken from Trask (1932). The water content of the sediments summarized in the table is based upon the difference in weight of the samples before and after drying at 105° for 24 hours.

The greater abundance of bacteria found in the finer sediments is attributed primarily to the higher organic-matter content of the latter although a multiplicity of other interrelated factors are involved. There would be a tendency for the bacteria in the "mobile layer" to be segregated with particles of similar size by the sorting action in sedimentation. (The average diameter of the bacteria is 0.2 to 1.2 microns.) Bottom-dwelling animals which not only compete with bacteria for food but also actually ingest large numbers of bacteria (MacGinitie, 1932) may help limit the bacterial populations in sand and silt. Disregarding colloidal deposits which occur mainly at the junction of the mud-water interface, more animals inhabit coarse deposits

TABLE 2. *Average nitrogen, water and bacteria content of sediment samples of different textures from the Channel Island region. (The data on the median diameter of the particles and the nitrogen content of the sand, silt and clay are taken from Trask, 1932.)*

Deposit	Median diameter of particles in microns	Nitrogen parts per 10,000	Water content in percent	Bacteria per gram (wet basis)
Sand	50–1,000	9	33	22,000
Silt	5–50	19	56	78,000
Clay	1–5	37	82	390,000
Colloid	<1	>100	>98	1,510,000

TABLE 3. *Relative number of different physiological types of bacteria found in the topmost 3 to 5 cm. strata of three representative marine sediment samples, the number being expressed as the reciprocal of the highest dilution in which the differential media showed their presence. A plus sign (+) indicates that the bacteria were demonstrated but their abundance not estimated.*

Sediment Sample No.	8160	8330	9309
Station location	32°51.2′N. 117°28.3′W.	33°25.9′N. 118°06.5′W.	33°44.2′N. 118°46.1′W.
Depth of overlying water	780 meters	505 meters	1322 meters
	Bacteria per gram of sediment (wet basis)		
Total aerobes—Plate count	930,000	31,000,000	8,800,000
Total anaerobes—Oval tube count	190,000	2,600,000	1,070,000
Ammonification—Peptone→NH_4	100,000	1,000,000	1,000,000
Ammonification—Nutrose→NH_4	10,000	1,000,000	100,000
Urea fermentation—Urea→NH_4	100	+	1,000
Proteolysis—Gelatin liquefaction	100,000	10,000,000	1,000,000
Proteolysis—Peptone→H_2S	10,000	1,000,000	100,000
Denitrification—NO_3→N_2	100	10,000	10,000
Nitrate reduction—NO_3→NO_2	100,000	10,000,000	10,000
Nitrogen fixation	0	0	0
Nitrification—NH_4→NO_2	0	0	0
Sulfate reduction—SO_4→H_2S	1,000	1,000	10,000
Dextrose fermentation	10,000	100,000	1,000
Xylose fermentation	10,000	+	10,000
Starch hydrolysis	10,000	100,000	10,000
Cellulose decomposition	1,000	+	1,000
Fat hydrolysis (lipoclastic)	1,000	+	+
Chitin digestion	100	+	+

such as sand or silt than fine ones like clay. Another factor is the oxidation-reduction potential and oxygen content both of which are lower in clay deposits than in silt or sand deposits. The low O/R potential retards the decomposition of organic matter and prolongs the viability of bacteria. Thus while bacteria may multiply very slowly in a clay having a low O/R potential, they may remain alive almost indefinitely. Finally the small particles of which colloids and clays are composed offer much more surface area than silt or sand deposits consisting of larger particles, and solid surfaces favor bacterial life (ZoBell, 1937).

Certain physiological types of bacteria were detected by inoculating selective media containing various substrates with

a little of the mud and testing for growth or chemical activity after several days incubation. Their relative abundance was determined by colony counts or by the minimum dilution method. Table 3 summarizes findings in the topmost 5 cm. of three representative cores. Most of the media provided for the activity of both aerobes and anaerobes.

Most physiological types of bacteria found in the core tops were also found in the core bottoms but in much smaller numbers. The distribution of all types was very uneven thus making generalizations difficult. However, the studies establish the fact that bacteria capable of activating many important chemical changes are widely distributed throughout the bottom deposits in significant numbers. A large proportion of the bottom-dwelling bacteria are proteolytic as indicated by their ability to liquefy gelatin and to liberate ammonia or hydrogen sulfide from proteinaceous materials. Bacteria have been demonstrated in the sediments which decompose amino-acids, urea and its derivatives, creatine, purine bases and various crude as well as purified proteins. The breakdown of these substances give rise to simpler compounds of nitrogen, sulfur, phosphorus and carbon, some of which may have considerable influence on the diagenesis of sediments.

Bacteria which reduce nitrates to nitrites and true denitrifiers which liberate free nitrogen from its compounds have received much attention from oceanographers ever since Brandt (1905) hypothesized that the productivity of tropical seas is limited by the activity of such bacteria. The problem was attacked with renewed vigor after Drew (1914) showed that under certain conditions denitrification is accompanied by the precipitation of calcium carbonate. According to Bavendamm (1932) who has summarized the literature on the subject, denitrifying bacteria are important geological agents especially in calcium carbonate precipitation in tropical seas. In the Channel Island region denitrifying bacteria are abundant in all sediments examined for their presence. However, neither nitrates nor nitrites have been detected. In fact it is doubtful if these compounds could exist in the reducing sediments. Certainly the low O/R potentials found here are not conducive to the generation of nitrites or nitrates by nitrifying bacteria. Nitrifiers were not found in the samples described in table 3 but they have been demonstrated in the topmost strata of seven of the 126 samples especially examined for their presence. Ammonium may be oxidized to nitrites and nitrates by nitrifying bacteria in the zone of the mud-water interface where oxygen is readily available from the overlying water but not in the sediments lacking oxygen. Thus it will be observed that various environmental conditions besides the mere presence of the necessary bacteria will determine whether either nitrification or denitrification will occur in bottom deposits.

Neither aerobic nor anaerobic nitrogen-fixers have been detected in marine bottoms of the Channel Island regions which are remote from possibilities of terrestrial contamination although Benecke (1932), Waksman, et al. (1933) and others have reported their presence elsewhere.

Saccharolytic bacteria are not as abundant as proteolytic species in the sediments. Most samples contained a few bacteria which produce acid and sometimes gas from the decomposition of sucrose, dextrose, maltose, xylose and arabinose. Starch-hydrolyzers were nearly as numerous as bacteria which attack the common sugars. Both aerobic and anaerobic cellulose-digesters occur regularly, the latter more frequently than the former. Such bacteria may explain the observation recorded by Trask (1932) that in recent sediments cellulose decreases in quantity from the surface downward usually being entirely lacking in ancient sediments. Some of the

anaerobic cellulose-digesters give rise to methane.

Lipoclastic bacteria which liberate the fatty acids from various lipids and utilize the glycerol are quite widely distributed in bottom deposits. They may play an important role in the genesis of petroleum. Most of them utilize the lower fatty acids but not the higher ones. Under the reducing conditions created by the bacteria the higher fatty acids are deoxygenated and they may be converted into long-chain hydrocarbons. Though lacking experimental proof, it is even possible that the unsaturated fats are converted into saturated hydrocarbons characteristic of petroleum by the combined activity of lipoclastic bacteria and those which reduce the O/R potential.

Bacteria which digest chitin can be demonstrated in most mud samples but their number is not great. Chitin is the highly refractile substance which constitutes the exoskeleton or carapace of most Crustacea and certain other marine organisms.

Neither yeast nor mold fungi have been demonstrated in the sediment samples. However, actinomyces-like organisms are commonly found.

SUMMARY

Viable bacteria have been demonstrated in 126 sediment samples collected in the Channel Island region along the coast of California some of which came from water exceeding 2,000 meters in depth. The number of bacteria ranged from a few thousand to several million per gram (wet basis) of sediment.

Profile series reveal a decrease in the number of anaerobic as well as aerobic bacteria with core depth.

The occurrence of strict aerobes at great depths in sediments lacking oxygen may indicate that such organisms have been buried there in a dormant state for a long time.

Sediment samples should be analyzed within a few hours after collection because their storage is accompanied by quantitative and qualitative changes in the bacterial flora.

Most of the bacteria are capable of multiplication at 0°C although the optimum is around 20°C even for those which have come from deep bottoms where the temperature is perpetually colder than 5°C.

Organic-matter content and particle size of the sediments are the chief factors which influence their bacterial populations. Neither distance from land, depth of the overlying water, temperature nor season seem to influence the distribution of bacteria in marine sediments.

Several different physiological types of bacteria have been detected which attack various substrates and produce certain end-products which may influence the diagenesis of marine sediments.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 1, PP. 19–33, FIGS. 1–10, APRIL, 1938

SEDIMENTS OF THE SUBMARINE CANYONS OFF THE CALIFORNIA COAST

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ABSTRACT

The sediments in the numerous submarine canyons off the California coast may be characterized as sand, mostly find sand, with an abundance of silt and some clay. They are in general very well sorted. Rock fragments and boulders have been dredged from many canyons. Bed rock crops out on the sides of Monterey, Carmel, and Scripps canyons. The median grain sizes in the canyons are slightly lower than on the adjacent parts of the shelf. There are variations in median grain sizes in the canyons but there is not always a decrease in median grain size with increasing depth. Short cores from Fire Hill canyon showed no stratification of the sediments. Heavy minerals make up only a very small part of the sediments. Authigenic minerals and organic material are common in the deeper portions of the canyons. The calcium carbonate content increases with depth due to the increase in abundance of organisms.

INTRODUCTION

Recent investigations of the continental shelf off the California coast show a great number of submarine canyons across the shelf and down the continental slopes. Some of these canyons head into major streams which extend far inland, others end abruptly at the coast where there are no nearby streams. The canyons are of dendritic pattern, V-shaped, sinuous course, and have steep slopes. The larger canyons are comparable in size and shape to the Grand Canyon and other large land canyons (fig. 2).

Dredging on the sides of these canyons showed croppings of bed rock at numerous points. The dredges brought up angular fragments of granite and conglomerate which appeared to have been freshly broken from the bed rock in the sides of the cayons. Dredges were frequently caught on the rocky sides and in some instances they were lost.

The "River-cut" theory of origin for the canyons is favored by Dr. F. P. Shepard, who has made a world-wide study of submarine canyons on the continental shelves and slopes. He has found that canyons off non-glaciated coasts have sinuous courses typical of river valleys in regions of high relief, a dendritic pattern, steep sides, and continue down the continental slopes with steep gradients.

Monterey canyon, which is the largest of the canyons off the California coast shown fig. 2, is a mile deep where it crosses the 100-fathom line. It appears to represent a major river valley system formed during a period of lowered sea level, possibly during Pleistocene time (1). The location of the most important canyons off the California coast are shown in Fig. 1.

Rock formations at the canyon heads. On shore at the head of Mattole and Delgada canyons near the northern part of the California coast, Upper Cretaceous marine sandstones and shales are present. Farther north are marine sands, sandy shales, gravels, and tuffs of Triassic age; unconsolidated sands, gravel, and clay of Quaternary age; and slates, cherts, limestones and sandstones with mica schists and serpentine of the Franciscan series.

Around the head of Monterey canyon the Quaternary and Triassic crop out. Just south and near the head of Carmel canyon are croppings of plutonic rocks; deep-seated granites, diorites, granodiorites, and gabbros. These croppings

continue into Monterey and Carmel canyons. Fragments of these rocks have been broken from the walls of the canyons and have been dredged from the bottom.

north of San Diego, California. From there to the Mexican border are Pliocene sands and sandy shales, Quaternary sands, gravels, and clays with narrow strips of Upper Cretaceous sandstones

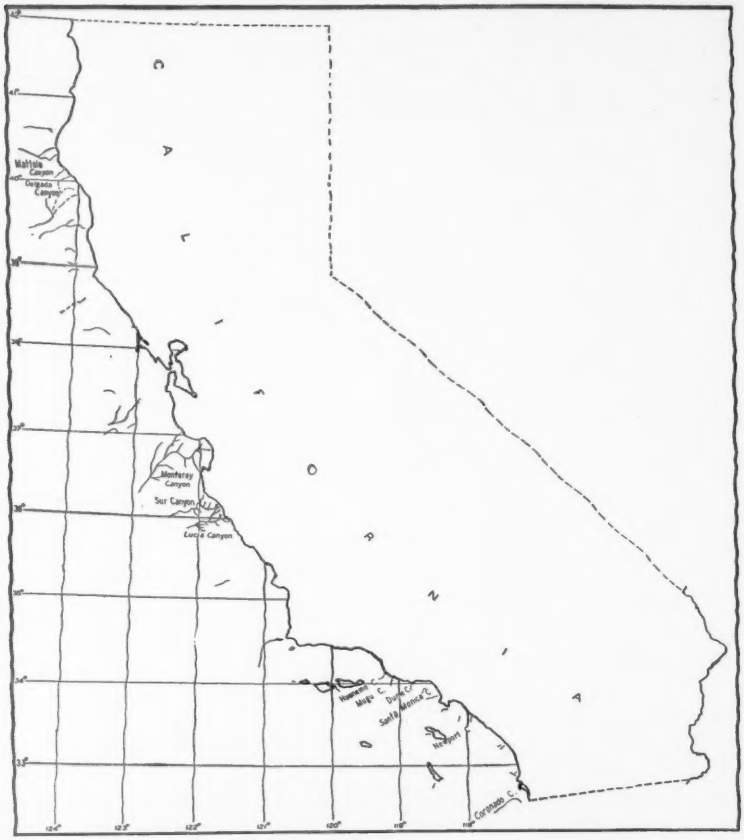

FIG. 1.—Location of important canyons off the California coast.

The rock formations occurring along the coast in the Channel Island region are Quaternary unconsolidated sands, gravels, and clays and Miocene sandstones and shales from San Louis Obispo Bay to a point about 35 miles

and shales south of La Jolla and on Point Loma.

The following formations are present at the heads of the canyons in the channel island region:

Hueneme—Quaternary; Mugu—Mio-

cene; Point Dume—Quaternary; Santa Monica—Quaternary and Miocene; Newport—Quaternary; Coronado—Quaternary and Upper Cretaceous.

Character of Sediments. The sediments may be characterized as sand, mostly fine sand, with an abundance of silt and some clay. Medium to coarse sand is found very near shore at the head of some canyons; farther out in the canyon there is a rapid decrease in the sand content of the sediment. In the outer part of the canyons the material is largely silt with sand and clay. The percentages of sand, silt, and clay in the samples from the canyons are given in Table 1. The character of the sediments suggests that the fine material carried into the canyons settles out in the deeper portions and on the continental slopes.

A few large rock fragments, rounded and angular, are present in some samples. Shells of Recent organisms are very common. The odor of putrifying organic matter was very pronounced in the samples from the deeper parts of the canyons.

Mechanical Analyses. Mechanical analysis was carried out by sieving the coarse material and pipetting the fine. The percentages of the different grain sizes were plotted in a cumulative curve on which the medium, first, and third quartile values were determined.

The median is the mid-point of the frequency distribution. Fifty per cent of the weight of the sediment is composed of particles larger in diameter than the median, and fifty per cent of particles smaller than the median. The medians of the samples from the submarine canyons were mainly silt and fine sand size (Table 1).

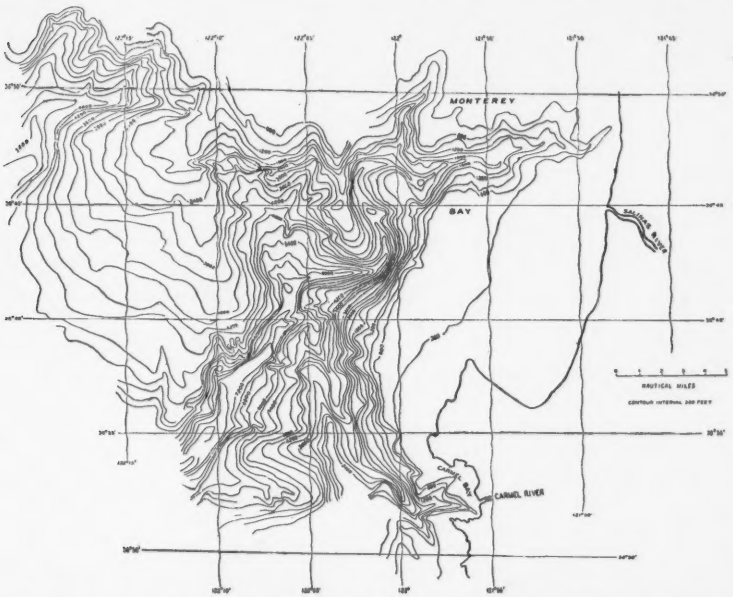

FIG. 2.—The submarine canyon which heads in Monterey Bay, California (9). Note the various tributaries which come into the main valley with the dendritic system of stream valleys.

TABLE 1. *Mechanical Analyses of Samples*

Canyon	Sample Number	Depth in Fathoms		Classification	Median	Coefficient of Sorting	Coefficient of Skewness	Per cent Sand	Per cent Silt	Per cent Clay	Latitude	Longitude
	1	3.0		Pebbles	2.000	1.00	1.00	100.0	0.0	0.0	36°31.6′	121°55.6°
	2	9.1		V.C.S.	1.320	1.32	0.87	98.7	1.3	0.0	36°31.6′	121°55.8′
	3	57.2		F.S.	0.130	1.80	0.88	77.0	23.0	0.0	36°31.7′	121°55.7′
	4	100.3		V.F.S.	0.075	1.63	1.13	56.5	43.5	0.0	36°31.7′	121°56.0′
Carmel	5	17.4		F.S.	0.175	1.44	0.87	70.0	30.0	0.0	36°32.1′	121°55.9′
	6	74.7		V.F.S.	0.068	1.92	0.93	25.0	68.2	6.8	36°31.8′	121°56.0′
	7	126.6		V.F.S.	0.072	1.65	1.26	54.6	45.4	0.0	36°31.9′	121°56.2′
	8	32.0		V.F.S.	0.095	1.46	0.94	75.5	24.5	0.0	36°32.0′	121°56.2′
	9	36.0		V.F.S.	0.078	1.52	0.95	60.3	39.7	0.0	36°31.7′	121°56.3°
	10	98.0		Silt	0.047	2.30	0.93	35.8	59.5	4.7	36°31.7′	121°56.5′
	11	36.0		Silt	0.025	1.92	1.00	12.6	86.8	0.6	34°05.7′	119°05.9′
Mugu	12	11.0		V.F.S.	0.066	1.48	1.11	52.0	48.0	0.0	34°05.3′	119°05.9′
	13	67.0		Silt	0.030	1.76	1.00	14.6	83.8	1.6	34°05.1′	119°05.3′
	14	195.0		V.F.S.	0.032	1.83	0.86	16.1	79.3	4.6	34°04.2′	119°45.3′
	15	9.0		V.F.S.	0.103	1.39	1.02	86.2	13.8	0.0	33°36.2′	117°55.7′
	16	19.5		V.F.S.	0.088	1.51	1.07	67.0	33.0	0.0	33°36.3′	117°55.9′
	17	28.0		Silt	0.040	2.00	1.34	37.5	59.8	2.7	33°36.1′	117°55.9′
	18	48.9		Silt	0.028	2.20	1.04	25.3	73.1	1.6	33°35.9′	117°55.0′
Newport	19	8.7		Silt	0.061	1.52	1.10	46.6	52.5	0.9	33°36.2′	117°56.0′
	20	14.7		V.F.S.	0.150	1.50	0.85	87.5	12.5	0.0	33°35.9′	117°56.2′
	21	20.0		Silt	0.049	1.44	0.95	27.8	71.3	0.9	33°35.8′	117°55.6′
	22	58.9		Silt	0.053	1.40	1.18	33.3	65.4	1.3	33°35.5′	117°55.8′
	23	51.4		Silt	0.048	1.32	0.93	22.1	76.0	1.9	33°35.2′	117°55.2′
	24	35.5		V.F.S.	0.093	1.31	0.89	79.9	20.1	0.0	34°00.1′	118°49.0′
	25	27.2		V.F.S.	0.085	1.30	0.92	76.6	23.4	0.0	33°59.9′	118°49.1′
Dume	26	38.2		V.F.S.	0.078	1.42	0.94	65.7	34.3	0.0	33°59.7′	118°48.9′
	27	158.5		Silt	0.045	2.10	0.96	37.0	57.5	5.5	33°59.6′	118°48.6
	28	11.0		Silt	0.052	1.52	1.05	7.5	90.3	2.2	34°08.5′	119°13.1′
	29	10.0		M.S.	0.375	1.37	0.94	92.7	7.3	0.0	34°08.9′	119°12.8′
	30	*7.0*		*Silt*	*0.052*	*2.32*	*0.65*	*58.7*	*41.3*	*0.0*	*34°08.4′*	*119°12.7′*
	31	15.5		V.F.S.	0.069	1.55	1.10	52.6	47.4	0.0	34°08.5′	119°12.9′
Hueneme	32	40.8		Silt	0.040	2.06	1.06	31.9	65.6	2.6	34°08.4′	119°13.1,
	33	14.0		Silt	0.048	1.39	0.90	24.6	74.0	1.4	34°08.3′	119°13.8′
	34	57.0		Silt	0.025	1.79	1.01	12.3	86.1	1.6	34°07.9′	119°13.6′
	35	88.0		Silt	0.031	2.04	0.63	7.2	91.2	1.6	34°07.8′	119°13.3′
	36	11.2		M.S.	0.300	1.47	0.84	91.2	8.8	0.0	34°07.6′	119°12.8′
	37	76.0		Silt	0.045	1.48	0.85	22.5	77.2	0.3	32°21′	117°17′
Coronado	38	158.0		Silt	0.032	1.81	0.70	6.0	87.2	6.8	32°21′	117°18′
	39	330.0		Silt	0.038	1.86	0.70	20.1	72.1	7.2	32°21′	117°21′
	40	85.0		Silt	0.046	2.14	0.48	9.2	89.7	1.1	40°06′	124°08.7′
	41	120.0		V.F.S.	0.069	3.00	1.15	40.5	53.2	6.3	40°05.3′	124°08.7′
Delgada	42	85.0		Silt	0.043	1.98	0.68	12.4	81.3	6.3	40°05.1′	124°09.4′
	43	281.0		Silt	0.046	1.94	0.72	13.6	77.5	8.9	40°03.3′	124°09.5′
	44	50. ±		Silt	0.030	2.56	2.66	24.4	67.2	8.4	40°03.6′	124°08.3′
	45	130. ±		Silt	0.034	2.12	1.30	11.1	81.7	7.2	40°02.7′	124°09.1′
Core No. 1		155.0	(Top)	V.F.S.	0.070	2.00	1.80	36.1	59.2	4.7	40°05.4′	124°08.6′
			(Middle)	Silt	0.059	1.98	1.95	31.9	64.5	3.6		
			(Bottom)	Silt	0.056	2.08	1.87	30.2	63.4	6.4		
Core No. 2		298.0	(Top)	Silt	0.058	1.93	1.86	31.3	65.6	3.1	40°02.9′	124°09.6′
			(Middle)	F.S.	0.175	1.33	1.00	76.9	22.4	0.7		
			(Bottom)	V.F.S.	0.063	2.24	2.00	39.8	54.3	5.9		
Core No. 3		200.0	(Top)	Silt	0.031	2.10	0.60	8.2	82.2	9.6	40°00.4′	124°09.6′
			(Middle)	Silt	0.033	2.34	0.50	11.4	66.9	21.8		
			(Bottom)	Silt	0.022	2.18	1.15	8.4	80.0	11.6		
Core No. 4		304.0	(Top)	Silt	0.060	2.46	1.57	37.4	54.1	8.5	40°06.6′	124°18.1′
			(Middle)	F.S.	0.138	2.40	0.48	54.1	38.6	7.3		
			(Bottom)	F.S.	0.140	2.28	0.61	54.6	43.1	2.3		
Core No. 5		263.0	(Top)	V.F.S.	0.082	2.24	1.00	41.0	51.8	7.2	40°07.4′	124°17.4′
			(Middle)	Silt	0.060	2.29	1.39	32.5	59.1	8.4		
			(Bottom)	V.F.S.	0.063	2.27	1.80	35.3	57.9	6.8		
Core No. 6		228.0	(Top)	Silt	0.044	1.98	1.25	22.3	75.3	2.4	40°08′	1°1246.6′
			(Middle)	Silt	0.035	1.77	0.83	5.7	90.2	4.1		
			(Bottom)	Silt	0.025	2.08	1.17	4.5	94.3	1.2		
Core No. 7		117. ±	(Top)	Silt	0.054	2.04	1.28	25.5	66.8	7.7	40°05.8′	124°16.1′
			(Middle)	Silt	0.048	2.80	0.87	25.0	67.2	7.8		
			(Bottom)	V.F.S.	0.063	2.20	1.25	33.4	60.4	6.2		

M.S. —Medium sand
F.S. —Fine sand
V.F.S.—Very fine sand

MEDIAN GRAIN SIZE AND THE RELATION TO DEPTH IN THE CANYONS

Delgada Canyon (fig. 3).—The sediment is very fine except very near the shore. On the other hand, the samples from the center of the canyons contain some coarse material. All but one of the samples show secondary maxima in the fine grain sizes. This condition suggests the settling out of fine material carried into the canyon and little or no transportation of material in the canyon.

Carmel Canyon (fig. 5).—Very coarse sand and gravel was found at the canyon head. There is a decrease in median size with depth, but this decrease is not progressive. The finest material was found in a canyon tributary.

Hueneme Canyon (fig. 6).—There is a slight decrease in median grain size with depth in the canyon. On the shelf on the east side the sediment is much coarser than in the canyon.

Mugu Canyon (fig. 7).—The medians of the samples from this canyons are almost equal and they are a little larger at a depth of 220 feet than near the head of the canyon at a depth of 45 feet. All of the samples show very fine material.

Dume Canyon (fig. 8).—The median grain sizes in the canyon are slightly less than on the shelf. This is due to the greater amount of silt in the sediment.

Newport Canyon (fig. 9).—The finest sediments in this canyon are found near the head. The material is slightly coarser

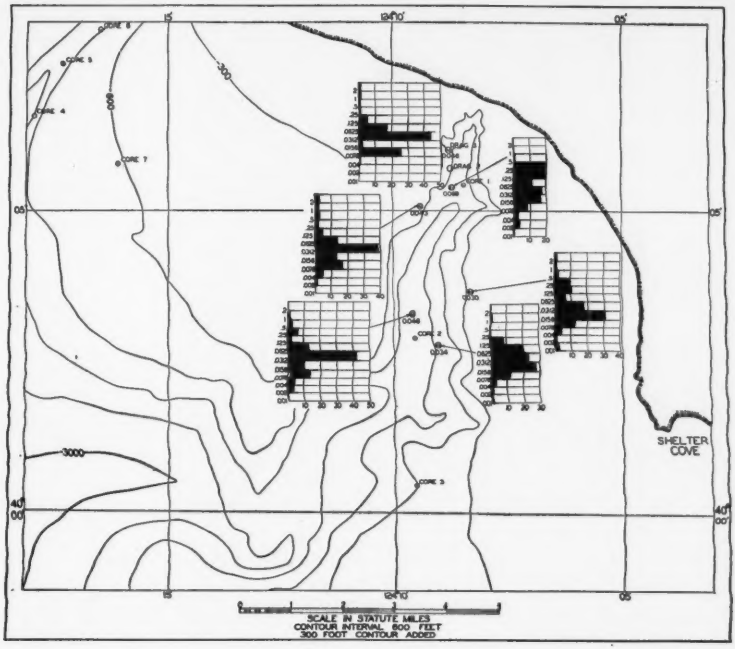

FIG. 3.—Histograms of samples and the locations of the cores taken in Delgada Canyon.

FIG. 4.—Location of dredges in Monterey canyon.

outside. No particular difference between the sides and bottom of the canyon was obtained.

Coronado Canyon (fig. 10).—The sediment is likewise very fine. There is little variation in median grain size from 500 feet to 1,650 feet. The median of the sample farthest out is slightly larger

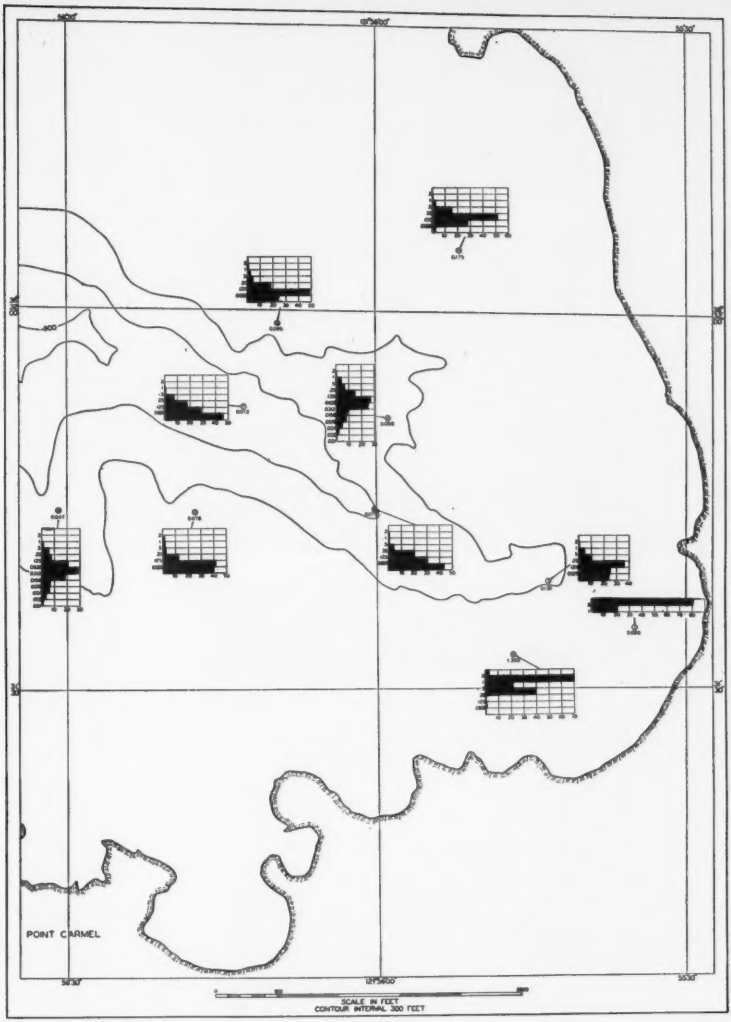

FIG. 5.—Histograms of samples from Carmel canyon.

than that of the sample at 1,250 feet and slightly less than the sample at 500 feet.

Summary. F. P. Shepard and G. A. MacDonald (2) have found there is no general decrease in grain size with an increase with depth on the shelf in Santa Monica Bay. The sediments in the submarine canyons show variations in

median grain size but do not always show a decrease with increasing depth. However, the median grain size in the canyons averages slightly lower than on the adjacent parts of the shelf. In some canyons the difference in median grain size is very small and is only slightly smaller than the median size on the sides of the canyon and adjacent parts of the shelf.

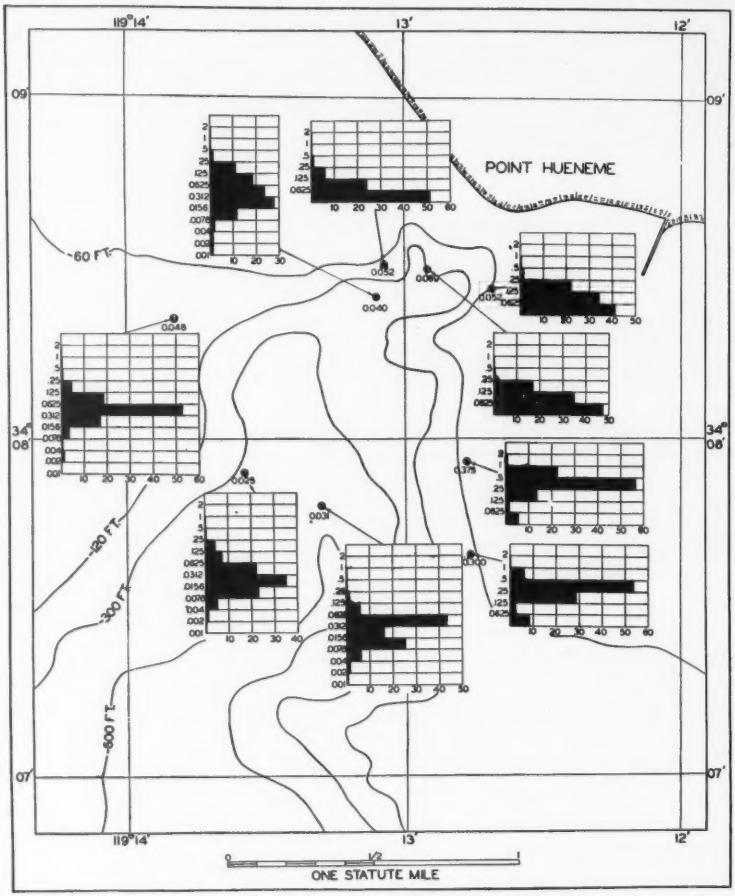

FIG. 6.—Histograms of samples from Hueneme canyon.

SORTING

Trask (3) states that the coefficient of sorting affords a mathematical measure of the degree of sorting of a sediment. It is based on the first and third quartiles, which refer respectively to the one-fourth and three-fourths divisions in the size distribution. The formula for determining the coefficient of sorting is

$So = \sqrt{Q1/Q3}$. When *So* is less than 2.5, the sediment is well sorted, and about 3.0 is normally sorted, with greater than 4.5 poorly sorted. The sediments in the submarine canyons are nearly all well sorted (Table 1). Most of the sediment was included in two or three grade sizes. Secondary maxima of fine material were common to some samples, and are shown in the histograms in figs. 3 through 10.

SKEWNESS

The coefficient of skewness (4) is a measure of the dissymmetry in the size distribution of the particles. This numerical value is obtained by the formula $Sk = Q1 \cdot Q3/M^2$. If the coefficient of skewness is greater than 1.0, the maximum sorting is on the fine side of the median, when less than one, the maximum sorting is on the coarse side of the

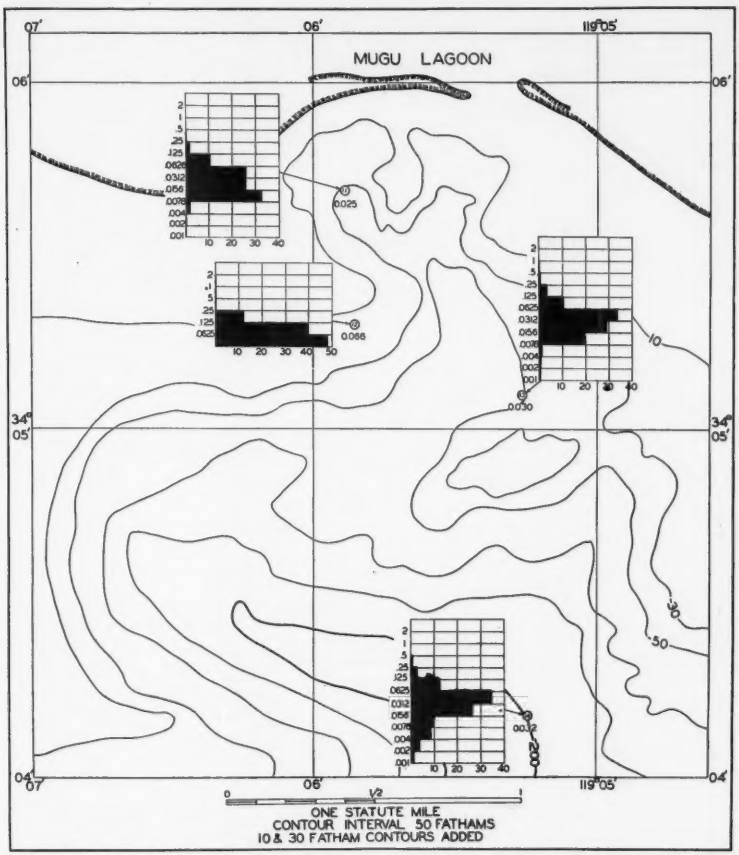

FIG. 7.—Histograms of samples from Mugu canyon.

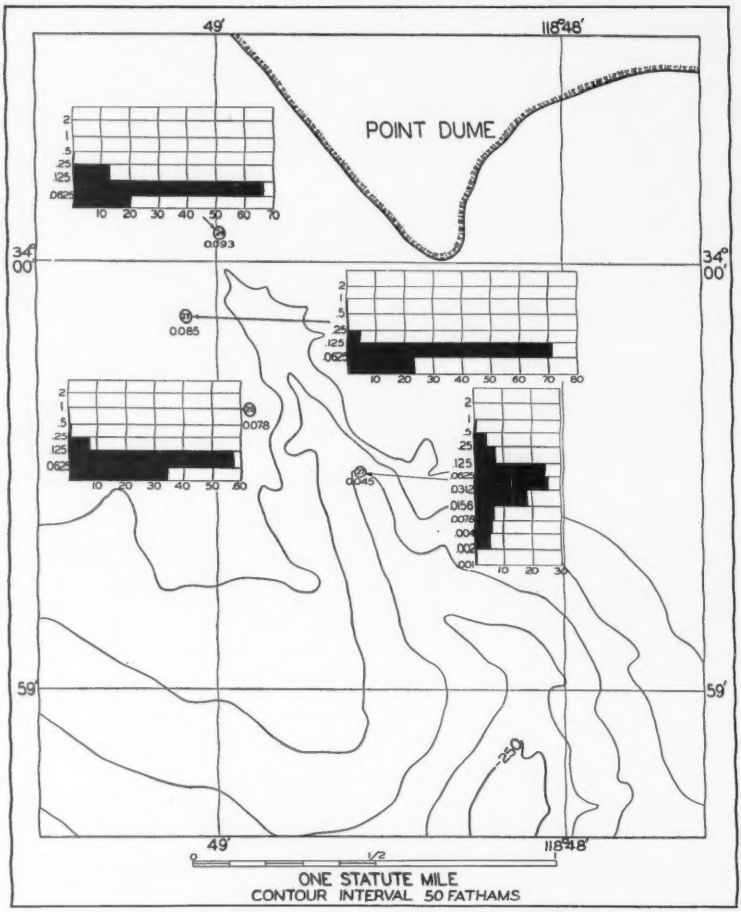

FIG. 8.—Histograms of samples from Dume canyon.

median, if about one, it corresponds to the median. The coefficient of skewness in the samples analyzed was usually about one, thereby corresponding to the median grain size of the sample (Table 1).

MINERAL CONTENT

Quartz is the most abundant light mineral in the sediments. Plagioclase and orthoclase feldspars are less abundant.

Heavy minerals make up only a small percentage of the sediments. Although a few samples vary from 1 to 10 per cent, the majority of samples contain less than 1 per cent. In the samples from the submarine valleys which contain a great quantity of silt and clay, the percentage

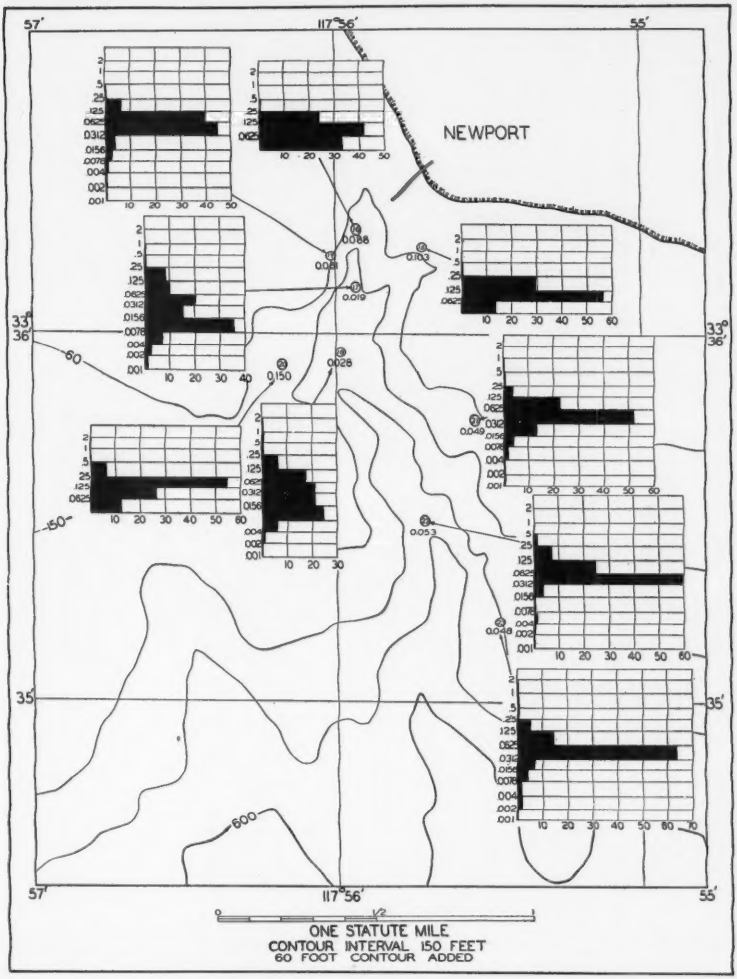

FIG. 9.—Histograms of samples from Newport canyon.

is very small as compared to that from the adjoining parts of the shelf.

The most common heavy minerals arranged in order of abundance found in the California submarine canyon sediments are hornblende, biotite, augite, hypersthene, diopside, epidote, apatite, magnetite, garnets, pink and colorless ilmenite, staurolite, titanite, zircon, sillimanite, anatase, pyrite (in only a few samples). In the samples from Carmel Canyon, biotite and hornblende are

especially abundant. In other canyons, the amount of biotite and hornblende is quite variable. Biotite was scarce in Delgada Canyon off the northern coast of California. Glaucophane, which is common in the Franciscan metamorphics on land along the coast (5), appears to have a wide distribution on the shelf, although it is not abundant.

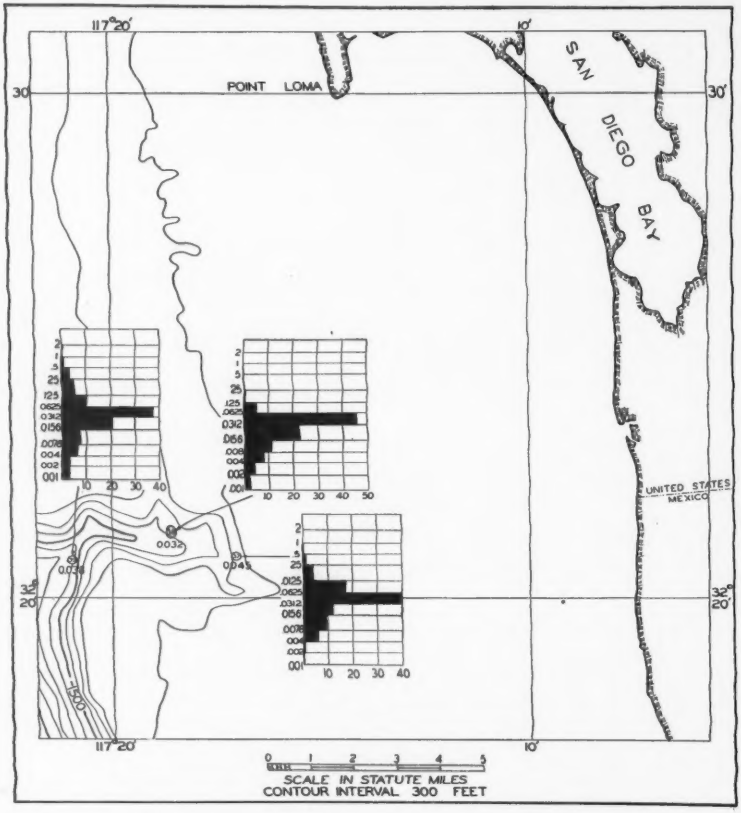

FIG. 10.—Histograms of samples from Coronado canyon.

AUTHIGENIC MINERALS

Authigenic minerals are rarely present except in the deeper parts of the canyons. Pyrite is common in the sediments in the deeper part of the canyons and is usually associated with foraminiferal remains. In some samples the tests have been entirely replaced with pyrite. It occurs less commonly as clusters of crystals. Glauconite is very rare and is found only in the samples from deep canyons off Redondo, Santa Monica, and Point Dume. In accordance with Galliher's theory (6) as to the formation of glauconite, no glauconite was found where there was much biotite and vice versa. Limonite is rare in the samples from near the head of the canyons.

CALCIUM CARBONATE

The calcium carbonate content of the sediments increases with depth due to the increase in the abundance of organisms which are largely Foraminifera. The sandy samples at the head of the canyons contain little or no calcium carbonate. In the deeper parts of the canyons down the continental slopes the organic remains compose as much as 13 per cent of the sediment. Trask (7) in his studies of the Channel Island Region off the coast of southern California found the same to be true, namely, that the calcium carbonate content is less in shallow water than in deep water and is as much as 16 per cent of the sediment in the deep Santa Cruz and Catalina basins.

ORGANIC REMAINS

Pelecypod and brachiopod shells and fragments are very common in the sediments. Pelecypod shells are the more abundant of the two. Foraminifera are especially abundant at the greater depths. Fragments of sponges were dragged from the bottoms of the canyons, and the spicules are quite common in the sediments. Calcareous worm tubes and sea urchin remains are also common. Bryozoa incrustations are abundant on the rock fragments dragged from the canyons.

Pelecypod shells and fragments of shells are abundant in the fragments of conglomerate which were dragged from the side of Monterey Canyon. The age of the conglomerate was determined as Pliocene. The large shells of the genus Pecten are common in the conglomerate. Some of the shells are excellently preserved.

Many of the samples from the canyons contain fragments of seaweed and the rock fragments have seaweed remains attached to them.

ROCK FRAGMENTS DRAGGED FROM THE CANYONS

The following types of rock were found on the sides of Monterey Canyon:

1. Conglomerate fragments having a fine sandstone matrix cemented with calcium carbonate. The fragments are partly perforated with holes formed by boring organisms. Bryozoa and sponges are attached to some of the specimens. Angular quartz pebbles with slightly rounded edges from one-fourth to 1½ inches in diameter are common in the conglomerate. Rounded and subangular basalt and siltstone fragments are also abundant. The siltstone fragments have light- and dark-green bands around each specimen which suggests a period of rest sufficiently long for chemical action to take place.

2. Siltstone fragments which measured 2 by 3 inches. These fragments are perforated by boring organisms. Each fragment is covered with a light- to dark-green weathered surface. They are composed of slightly coarser particles than those found in the conglomerate.

3. Limestone, black, non-crystalline, very silty, rounded fragment 5 by 3 inches in size, and perforated.

4. Sandstone fragment 3 by 2 inches, loosley consolidated and cemented with calcium carbonate. Masses of green biotite with rounded edges are abundant.

5. Chert fragments measuring 1 to 2 inches both rounded and angular. Dark-gray to black and reddish-brown varieties were found.

6. Vocanic ash; buff-colored rounded fragments.

7. Granite, biotitic, very coarse grained. The fragment is 2 by 3 inches in size and well rounded.

8. Granite porphyry, well-rounded fragment having large feldspar crystals embedded in a fine-grained matrix.

The following rocks were dredged from Carmel Canyon:

1. Biotitic granite, angular fragments measuring 4 by 6 inches. The outer surfaces are stained with limonite which comes from the weathering of the iron in the biotite. Organic structures are attached to the outer surfaces of the fragments.

2. Siltstone, very coarse, hard, has numerous broken sponge spicules at-

tached. The fragments measure 5 to 7 inches.

3. Silty clay fragments, very compact. The fragments which measure 3 by 4 inches are perforated by organisms.

The angular fragments of granite dredged from Carmel Canyon have freshly broken surfaces which suggests that they were broken from solid rock on the sides of the canyon. The outer surface of the fragments are weathered and the minerals have undergone partial decomposition.

Delgada Canyon. The dredges in this canyon collected abundant pelecypod shells, some brachiopod shells, calcareous worm tubes, and sponges. Included in the dredges are a few partly consolidated silty clay materials which were disintegrated by washing. Some of the samples collected in the canyon contain a few subrounded to rounded basalt pebbles one-fourth to one-half inch in size.

CORES FROM FIRE HILL CANYON

Seven cores were taken in Delgada Canyon (fig. 1), the recovery in each core containing about one foot of material. According to Wrath's (8) work on the compaction of sediments in core sampling, the recovery represents about one-half of the thickness of material penetrated by the coring apparatus. Wrath found that under the condition of soft mud over sand, the compaction was 45 per cent, soft mud 52 per cent, sand 35 per cent, and sandy silt 48 per cent.

The cores were examined for stratification and none was observed; however, there was a slight difference in grain size throughout some of the cores which could be observed before mechanical analyses were made.

Mechanical analysis (Table 1) were made of the top, middle, and bottom of each core. Although there is no great difference in the median grain size noted between the top, middle, and bottom of each core, there is a strong difference in core No. 2 where the median grain size of the middle is much larger than the top and bottom. The percentage of sand, silt, and clay is rather uniform from top to bottom in all but two of the cores.

ACKNOWLEDGMENTS

The writer is indebted to Dr. F. P. Shepard for the samples used in the study, for data regarding the character of the continental shelf and submarine canyons off the California coast, and for his valuable suggestions in the study of the sediments and in the preparation of the manuscript. The writer is grateful to Mr. K. O. Emery for his assistance in the preparation of the figures used in the manuscript and to Mr. W. F. Wrath for his assistance in the analysis of the samples.

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JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 8, NO. 1, PP. 33-35, APRIL, 1938

TRANSPORTATION OF SEDIMENTS ON FRESH-WATER SURFACES BY FLOTATION

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ABSTRACT

Patches of sand are often found floating on the surfaces of fresh-water lakes. Most of this sand is between 0.297 mm and 0.84 mm in diameter but a few of the grains are considerably larger.

Examination of the floating sand under the microscope shows that it floats because of surface tension of the water and the resistance of the sand grains to being wetted. The finer material, if of equal angularity, floats somewhat more readily than does the coarse. This may be a factor in the gradation of the sand on the lake bottom.

If small waves are present the sand is picked up almost constantly and the material floats for long distances. The amount which moves out from the lake shores in this way is considerable and is probably an important factor in lake filling.

Sand floating on the surface of water has been mentioned and discussed by a few observers (1) but, in general, students of sedimentation seem to consider this method of transportation of little importance. However, observations made during the past summer on some of the lakes of Michigan indicate that the carrying of sand outward from the shore by this process may, under certain conditions, be far from insignificant.

On lakes having sandy shores brownish patches up to several inches in diameter may often be seen floating on the surface of the water. These consist of sand that remains suspended on the water because of surface tension. They are easily collected in a partly submerged milk bottle and by shaking the bottle the sand at once sinks to the bottom and the water can be poured off. About half a pint, 404 grams, was collected in this way from the surface of Duck Lake and nearby smaller ponds near Whitehall, Mich.

This sand when thoroughly dried and placed in sieves on a mechanical sorter and agitated for twenty minutes gave the following result:

Retained on the 0.84 mm screen	5.70 grams.
Retained on the 0.297 mm screen	388.51 grams.
Retained on the 0.147 mm screen	9.60 grams.
Retained on the 0.104 mm screen	0.07 grams.
Retained on the 0.074 mm screen	0.01 grams.
Total	403.89 grams.

A similar analysis of an equal amount of sand taken at random from the shores of the lake gave the following:

Retained on the 0.84 mm screen	0.22 grams.
Retained on the 0.297 mm screen	292.65 grams.
Retained on the 0.147 mm screen	110.61 grams.
Retained on the 0.104 mm screen	0.77 grams.
Retained on the 0.074 mm screen	0.06 grams.
Total	404.31 grams.

None of the material retained on the 0.84 mm screen is larger than 4 mm in diameter and most of it does not exceed 2 mm. Most of the particles are quartz but the larger ones are fragments of shale.

Comparison of the two tables shows that a larger amount of sand above 0.84 mm is found in the floating sand than in the check sample. This is probably explained by failure to take an entirely representative check sample. It will be noticed that by far the greater amount of the floating sand is above 0.297 mm, whereas in the check sample about one-third as much is retained on the 0.147 mm screen as on the 0.297 mm screen. Considerably more material of the check sample is retained on the 0.104 mm and 0.074 mm screens than of the collected sample although the amount is small in both cases. This absence of the finer sand in the floating material may probably be explained by the way in which the water picks up the sand.

The sand is mostly derived from dunes and the surfaces of a considerable percentage of the grains are frosted. Most of the grains are subangular although many are well rounded. Possibly 20 to 25 per cent of the grains show fractured surfaces. The collected sands retained on the 0.104 mm screen are more angular than those of any other fraction and are mostly composed of quartz, whereas those of the check sample of the same dimensions are more rounded and are mostly magnetite and other heavy black minerals.

No amount of stirring of the sand on the bottom of the lake causes any of it to be suspended on the surface, therefore its flotation is not the result of a jelly-like substance such as that found by Raymond and Stetson in ocean water (2).

It is noticeable that gentle waves such as those caused by a person wading will, when they reach the shore without breaking, lift and float patches of sand. Also when handfuls of sand from the bottom of the lake are lifted above the water and gently lowered beneath the surface patches of sand are caused to float. A handful of sand can be repeatedly raised and lowered and will continue to give off floating sand patches until it is entirely washed away. As is to be expected, damp sand from the shore at the water line gives the same result, and dry sand lowered into the water in the same way gives a somewhat greater amount of suspension.

It is found that if either wet or dry sand is allowed to run through the fingers and drop on the water up to a height of about 3 inches, some sand will float on the water but not nearly so much as when the sand is gently lowered. At heights greater than 3 inches none floats except a little of the finer dry sand.

Small waves such as those made by a person wading causes some of the sand to drop from the floating patches and quick, sharp waves, such as can be caused by the hand in the water, makes much of the sand drop quickly from the patches. It thus appears that floating sand may not be carried through areas of sharp or breaking waves. Further observation established the fact that sand is never floated where waves are breaking.

Observation also shows that the amount of sand floated would be much greater if it were not that after small wavelets reach the beach continuously for a considerable time they acquire all available sand and the action ceases until heavier waves work the sand over at the water's edge so as to expose another supply.

Although it appears that the finer sand floats more readily than does the coarser, if of the same degree of angularity, and is probably picked up earlier, the failure of the wavelets to continue to pick up material on an undisturbed shore is probably the result of the position of the remaining sand grains combined with an adjustment of the shore slope. The free sand grains are more easily picked up whereas better interlocked grains are more difficult for the water to remove.

Also, observation shows that the flatter the slope on to which the waves move the more readily the sand is floated.

In order to test, to some extent, the distance floating sand may be carried patches of it were followed in the stream that flows out of Duck Lake into Lake Michigan, a distance of nearly 600 feet. It was found that the sand patches floated into Lake Michigan with comparatively little loss. Probably 80 per cent of the sand that started reached the lake. In places the sand patches floated through ripples of considerable size but suffered little loss so long as the ripples were smooth. Some sand was being transported down the stream in this way during all the time of the period of observation.

On the west side of Duck Lake the winds are usually from the west, off Lake Michigan. This results in relatively calm water near the shore. Here sand patches are almost constantly being carried out into the lake. Many of these were seen to drift outward from the shore for 100 to 200 feet before being lost to sight in the rougher water. Observations of various other lakes that range in area from very small to 5 or 6 square miles showed drifting sands on all of them. Floating sands were seen a few times on Lake Michigan but generally there is too much surf on the beach for the sand to be picked up.

Examination of the surfaces of some of the larger lakes by boat showed that sand is carried in this way for considerable distances. On White Lake, after several hours of light steady wind, floating sand patches were found a half mile or more from shore, and on Crystal Lake near Frankfort, Mich., they were found 1½ miles from shore.

Examination of a mass of floating grains under the microscope showed that each grain floats about nine-tenths submerged with the surface above the water dry. The grains have considerable buoyancy and are somewhat difficult to sink. As soon as a grain is completely moistened, however, it immediately drops to the bottom. Simonds (3) in his experiments found that angular grains float more readily than round. He believes the cause of this to be rolling and consequent complete wetting of the round grains when dropped on the water, whereas angular ones have less tendency to roll.

Although observations in both the field and laboratory show that the water will carry very coarse material under favorable conditions it is believed the finer material, because of the greater ratio between its surface and mass, is more easily lifted and carried farther. If so, the process has a sorting effect which is probably a factor in grading the bottom material from the shore outward.

The total amount of material transported in this way from the sandy shores of the lakes must be very great since it seems to be going on most of the time. That the amount must be considerable is shown by the fact in about 3 hours a half pint was collected in a milk bottle. It is entirely possible that the sand carried out into a lake in this way may be in some cases as great a factor in filling its basin as the material dropped directly by the wind.

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HAULTAIN, H. E. T., *Splitting the Minus-200 with the Superpanner and Infrasizer*, Transactions, Canadian Institute of Mining and Metallurgy, vol. XL (1937), 229–240.

Scientists often regret that the present growth of knowledge prevents any one man from knowing well more than a special branch of learning. Often those approaching a given problem are unaware of what has been done on the matter by workers in another field. Problems concerning mechanical analysis of sediments are closely related to those of sizing and classifying in ore dressing, yet workers in either field seem to have made little use of the other's work, and in some cases do not seem to be aware of the interrelation. Thus, not one of 186 titles in a recent bibliography of mechanical analysis by Krumbein is from the literature of ore dressing.

This work here reviewed presents information of considerable importance in the analysis of fine-grained sediments. In studying gold ores from Kirkland Lake, Ontario, it became necessary to separate very fine auriferous telluride particles. This problem was solved by the development of the Superpanner, which consists of a specially shaped pan supported on a mechanism which gives the desired motion, viz., a combination of an end bump and a gentle side shake. The mechanism is so designed that adjustments of eight variable factors may be made quickly and easily during operation. A very clean separation of a heavy concentrate and lighter tailings results. Material ranging in size from 65-mesh[1] to 14 microns, and in some cases still finer material, may be treated. During practical investigations of gold ores at the Lake Shore mines it was found that "The Superpanner produces good quantitative results down to at least 14 microns and occasionally to 10, and qualitative results on all sizes." The machine would evidently be useful in concentrating for study minerals of small diameter where a sufficient specific gravity difference exists.

The urgent need of size analysis of fine material in connection with the production of sized fine abrasives, and with grinding studies led to the development of the Infrasizer, an apparatus which can separate comparatively large quantities of minus-200 mesh material into any desired number of grades. The apparatus is essentially an air elutriator. It consists of seven conical tubes or sorting columns, connected in series, the largest of which discharges into a dust collecting bag similar to those used on vacuum cleaners. The tubes are suspended from a bar which is raised and dropped by a cam, the distance and frequency of dropping being fixed. Air from an ordinary compressed air line is found satisfactory, pressures of 4 or 5 pounds per square inch being used.

In the development of the apparatus to its present form several difficulties had to be overcome. A discussion of these seems in order as the best means of answering the queries which come to mind concerning the utility of the apparatus. The first of these was the tendency of the fine particles to flocculate. This was dealt with by converting the upper portion of the cylindrical hole in the rubber plug at the base of the sorting column into a cone and resting therein a golfball. The air carrying the particles passes as a thin, high-velocity stream between the cone and ball and this, combined with the wabbling, rotatory motion of the ball tends to tear the particles apart. Material which slides back down the tube is scrubbed by the jets of air around the ball. This combination has proved an efficient particle separator, which does not seem to wear down the particles by attrition. Second was the

[1] References are to the Tyler screen scale throughout.

difficulty of producing uniform upward flow in the sorting column. It was found that no provision for this was necessary. In other words, accurate classification is actually obtained in turbulence, notwithstanding usual classification theory. It was necessary to hold constant the volume of air passing through the columns, and this was accomplished by air pressure and volume controls which keep the volume constant with varying supply and back pressures.

As to results, the workers at Lake Shore referred to above state: "The Infrasizer gives an uncannily accurate sizing in quantities large enough for accurate assays (8 to 20 assay tons)," (1 assay ton is 29.166 gms.). Kaultain used throughout the term "nominal microns" since he is unable to arrive, "with any degree of useful accuracy, at the average diameter of these particles. Measurement under a microscope would result only in a very rough approximation." He demonstrates the accuracy obtained by a series of photomicrographs showing remarkably good sizing even down to minus-10 microns (nominal) grade, and by the results of three typical runs in which the per cent of minus-28 microns (nominal) in 3, 3, and 5 consecutive tests had average deviations of 2.2, 12, and 2.9 parts per thousand respectively.

Experimentation is still proceeding. It has been found that 40 (nominal) microns correspond closely to 325-mesh (nominal width of opening 43 microns). The diameters of the tubes vary as the square root of two, resulting in a similar variation in the average diameters of succeeding products, as in the Tyler scale. It is hoped by calibration of the results of a standard type of Infrasizer to "do for the minus-200 what the Tyler screens have done for the coarser material."

Professor Haultain states that to ensure reliable Superpanners and Infrasizers he has arrangements under way whereby they will be designed, constructed, and tested under his personal supervision.

It appears to this reviewer that these machines, and in particular the Infrasizer, represent a valuable addition to the technique of mechanical analysis. For most work the methods outlined by Krumbein and others are probably the best, but as a means of accurate work and of checking other methods, the Infrasizer stands unique.

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Report of the Committee on Sedimentation, 1936–1937. Parker D. Trask, Chairman. Division of Geology and Geography, National Research Council, October, 1937.

The report of the Committee on Sedimentation for the period ending July 1, 1937, contains the report of the Chairman and nine additional contributions, as follows:

Sedimentation Studies by the Soil Conservation Service, Carl B. Brown.

Research of Sediments by British Scientists during 1934–1936—Henry B. Milner.

Mineralogy of Sedimentary Rocks—F. J. Pettijohn.

Monogram for the Settling Velocity of Spheres—Hunter Rouse.

Bibliography on Roundness and Shape of Sedimentary Particles—R. Dana Russell and Ralph E. Taylor.

Terminology of the Fine-Grained Mechanical Sediments—W. H. Twenhofel.

The Bottom Sediments of Lake Monona, a Fresh-water Lake of Southern Wisconsin—W. H. Twenhofel.

A Hydraulic Coring Instrument for Submarine Geologic Investigations—Fred M. Varney and Lowell E. Redwine.

Classification and Selected Bibliography of the Surface Textures of Sedimentary Rocks—Lou Williams.

The report should be of great interest to students of sediments and as similar reports in the past it records some of the advances in the field of sedimentation.

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